# Protected areas and climate-mediated avian range shifts: a case study for a breeding species in the Upper Great Lakes region

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## Abstract

While protected areas are widely regarded as a cornerstone strategy of conservation, their robustness as climate change refugia remains uncertain. This question is particularly salient in heavily patchworked landscapes such as those of the Midwestern United States, where land cover, land use, and climate interact to create habitat heterogeneity on both fine and large scales. Using detection/non-detection data from the Wisconsin Breeding Bird Atlas, an eBird-integrated citizen science initiative, we evaluated whether the total extent of protected area coverage in a survey unit (Atlas block) influenced range-shift dynamics of a breeding species, the Red-bellied Woodpecker *(Melanerpes carolinus)*, between two temporally distinct Atlas periods. We modeled apparent colonization and extinction as proxies for shifts to the breeding range with binomial generalized linear models, evaluating support for protected areas while controlling for land cover, climate, and effort across two differentially filtered survey unit subsets. Preliminary results suggest protected areas do not play a substantial role in modulating range shift dynamics for our proof-of-concept species. Our regional assessment provides insight as to whether current protected area approaches modulate species breeding range distributions under climate change, while also highlighting how analytical decisions around skewed effort data can influence inference drawn from Breeding Bird Atlas data.

*Keywords: birds, breeding bird atlas, citizen science, climate change, eBird, generalized linear models, Melanerpes carolinus, model selection, protected areas, range shifts, species distribution models, Red-bellied Woodpecker*

## Introduction

Protected areas, broadly defined as locales designated and/or managed to achieve specific conservation objectives, figure prominently in conservation worldwide, including as a strategy of climate-change adaptation (Joyce et al. 2009, Griffith et al. 2009, Gaston et al. 2006, Elsen et al. 2020). The number of protected areas continues to grow, with coverage increasing from 3% of the world's land area in 1990 to over 16% in 2021 (IUCN 2020). A pressing question, however, is whether protected areas can maintain and protect biodiversity in the face of modern climate change, as positive conservation outcomes may no longer be ensured (Hannah et al. 2007, Virkkala et al. 2014). While protected areas generally support higher species richness and species abundances as well as lower extinction rates (Watson et al. 2018, Watson et al. 2014, Gillingham et al. 2015), recent species declines and losses within protected areas are not uncommon (Albuquerque et al. 2013, Barnes et al. 2016).

In North America, novel anthropogenic threats—ranging from habitat loss to climate change—have culminated in the loss of nearly three billion birds since 1970 (Rosenberg et al. 2019). Continental trends in climate across the Midwest have exposed bird populations to unprecedented warming, altered precipitation patterns, and a higher frequency and intensity of extreme weather (Kunkel et al. 2013, Pryor et al. 2014), forcing many species to shift their ranges (Zuckerberg et al. 2009, Germain and Lutz 2020)--and leading to a novel conservation dilemma for many conservation agencies.

State, federal and nonprofit groups alike invest significant resources in support of protected area-based conservation approaches (Joyce et al. 2009, Griffith et al. 2009, Rannow et al. 2014). The rate and complexity of modern climate change imposes significant uncertainty on the effectiveness of protected areas in safeguarding vulnerable species, and a unified understanding is necessarily confounded by questions of scale and regional variability (Gillingham et al. 2015, Peach et al. 2019, Dobrowski et al. 2021, Parks et al. 2022). In the Midwest, where species navigate a complex patchwork of public and private lands, a region-specific assessment of range shifts is essential for evaluating protected areas as climate change refugia and guiding conservation entities toward more informed, future land acquisition.

Here, we offer a case study for the Red-bellied Woodpecker (*Melanerpes carolinus*) using data from the first (1995-2000) and second (2015-2019) Wisconsin Breeding Bird Atlas (WIBBA); these methods can be likewise applied across other grid-based biodiversity assessments. Across two experimental “comparable” block sets, we modeled species apparent colonization and extinction as a proxy for shifts to the breeding range using binomial generalized linear models. Because temporal effort from the first WIBBA was recorded inconsistently, it was necessary to devise a different metric of survey effort, or completedness, for inclusion in models: we chose the difference in species richness per block per atlas period as a simple proxy. Our goals were 1) to discern any modulating effect of protected area on species range shifts (ie. buffering extinction, promoting colonization), 2) examine the usefulness of a highly simplistic survey effort proxy across two different sample unit subsets, and 3) provide proof of concept for these methods to address range shifting of any breeding species within the Upper Great Lakes region (Michigan, Minnesota, Wisconsin) in future work.

## Materials and Methods

### *Breeding Bird Atlas Data*

Breeding Bird Atlas (BBA) programs across the United States enlist volunteer surveyors (“Atlasers”) to document breeding species in state-wide, multi-year efforts. Atlas surveys are conducted in multi-year “periods”, which generally number 4-6 years apiece, and are repeated approximately every 15-20 years with the goal of discerning distributional change over time. Within periods, Atlasers contribute semi-structured effort (in the form of “checklists”) to structured survey units (“atlas blocks”) across a systematic grid covering a state’s geopolitical extent.

Within a block, Atlasers assign “breeding codes” to species for which they observe evidence of breeding; these codes reflect the likelihood of a species’ local reproduction based on a hierarchy of behaviors: Possible (e.g. species observed in appropriate habitat or singing male), Probable (e.g. pair observed in suitable habitat in breeding season), and Confirmed (e.g. nest with young). By design, only the observation with the highest-level breeding code per species per survey is retained in the final BBA dataset. Following the logic of Sadoti et al. (2013), we considered all three levels of evidence to represent “breeding presence” at the atlas block scale, contextualizing our data within a detection/non-detection (0, 1) framework suitable for logistic regression.

We extracted all checklists from the first (1995-2000) and second (2015-2019) Wisconsin Breeding Bird Atlas (WIBBA) from eBird, subsetting records to the North American breeding season (May-August) using the R and the auk package (R Core Team 2024) (Strimas-Mackey et al. 2025). Details relevant to the WIBBA design and protocols are described in Cutright et al. 2006, Smith 1990, and Anich and Prestby 2026.

### *Atlas Block Sets*

The strength of Breeding Bird Atlases (BBA), and citizen science initiatives in general, is the sheer amount of data accessible to researchers–the tradeoff, of course, is the extra consideration researchers must then give to discerning “good” data. Variation in survey effort/completedness is one common, notable feature of datasets collected by volunteer populations with which analysts must contend, as inference from citizen science initiatives like BBA is often sensitive to decisions surrounding survey effort and block inclusion (Smith 1990, Cutright et al. 2006, Sadoti et al. 2013, Peach et al. 2019).

Although the Wisconsin BBA employs a “Priority Block” system designed to produce a robust subset of comparable blocks for analysis, many “non-Priority” blocks also receive substantial survey effort, and completion thresholds set for Priority blocks may unduly reduce overall sample size and statistical power. To assess the sensitivity of inference to block-selection criteria, we therefore analyzed two alternative comparative block sets subsetted from the full Atlas block pool (N = 7056). The first, provided by partners at the Wisconsin Department of Natural Resources, represents a heavily filtered subset (“DNR” set; n = 858) wherein blocks met predefined completion criteria. The second, constructed in-house, represents a minimally filtered subset (“RLL” set; n = 3337), wherein we retained blocks regardless of predetermined completion thresholds, resulting in a subset with a wide range in survey effort among blocks and periods. Neither block set is assumed to represent a “true” standard of effort, rather, they bookend a plausible range of filtering stringency. All analyses and further subsetting were conducted independently for each block set.

### *Example Species*

We model detection/non-detection data for the Red-bellied Woodpecker *(M. carolinus),* a Wisconsin breeder that has undergone recent northward range expansion in the Upper Great Lakes region (Stallworth et al. 2025) and is well-represented in both block sets.

### *Covariates*

We quantified a number of land cover, climate, and survey-effort covariates at the block level. Land and climate covariates were summarized as both long-term averages and between-period differences.

We extracted 15 land cover types from the National Land Cover Database (U.S.G.S. 2024a) and summarized for each the percent cover per block. We constructed both a baseline cover covariate, i.e. percent coverage by land class type for a single reference year between the two Atlas periods (2008), and a cover difference covariate, i.e. the percent difference in coverage between the first year of each Atlas period (1995 and 2015). We also constructed a number of grouped land covariates (e.g. developed total = sum of all four developed landcover classes) to be used on a species-specific basis in model simplification and selection.

We derived three climate covariates (temperature minimum, temperature maximum, and precipitation) from Daymet monthly gridded climate data (Thornton et al. 2022) for the breeding season (May-August). We constructed per block monthly averages that were further grouped into summer season per block averages, and then into per period block averages. Again for each variable we calculated both a baseline, ie. long-term monthly average (38 years), and a difference, ie. anomaly (18 years prior to the beginning of each Atlas), among blocks per period.

Finally, we compiled protected areas (PA) within the state of Wisconsin from the Protected Area Database of the United States (U.S.G.S. 2024b), and summarized PA as proportional coverage of each Atlas block; we considered PA stable across both Atlas periods.

***Survey Effort, Completeness, and Imperfect Detection***

Structured, repeat surveys are not a built-in component of most BBA frameworks, including WIBBA. In addition, temporal effort metadata were missing or unreliable for much of the first WIBBA due to the analog nature of data collection at the time, which contrasts today’s fully integrated, digital BBA-eBird interface.

These limitations precluded the use of traditional occupancy modeling frameworks, as well as time-based effort-control covariates commonly employed to account for imperfect detection inherent with “incomplete” survey effort (Mackenzie et al. 2003, Link and Sauer 2007, Guillera-Arroita 2017, Wilson et al. 2017). While some recent work has taken a space-for-time substitution or single-visit dynamic occupancy model approach to meet the challenge of skewed and/or missing effort (Sadoti et al 2013, Peach et al. 2017), such approaches require assumptions about detection and closure we did not feel confident making with historical Atlas data (Tingley and Beissinger 2009).

Thus, we took a highly simplified approach to partially account for variation in survey effort by including the change in total species richness per block between Atlas periods (Supplemental Figure S1) as a model covariate. Species richness is highly correlated with survey effort and thus may serve as a highly relevant, structurally related effort proxy. While imperfect, this proxy does allow relative differences in survey effort to be controlled consistently across Atlas blocks and periods, especially when paired with our dual block subset design.

***Model Construction and Selection***

We used generalized linear models with a binomial error distribution within the R statistical software (R Core Team 2024) to evaluate the relationships between protected area coverage and the probability of colonization or extinction at the level of Atlas block (5 x 5 km). A species with breeding presence in an Atlas block in (ie. coded as Possible, Probable, or Confirmed) was considered present/detected (1); any species "un-coded" was considered absent/undetected (0).

We constructed separate response datasets for apparent colonization and extinction from the first to second Atlas, with colonization data (0, 1) grouped with absence data (0, 0) and extinction data (1, 0) grouped with persistence data (1, 1)--this construction conditions the model response around the second period detection. For example, if a species was not present in a block in the first Atlas (0), can protected area coverage account for either a change in distribution (0 to 1) or the species remaining absent? This formulation results in four unique model contexts per species:

1) Species x Colonization/Absence x RLL Block Set
2) Species x Extinction/Persistence x RLL Block Set
3) Species x Colonization/Absence x DNR Block Set
4) Species x Extinction/Persistence x DNR Block Set

We defined an initial full model that included ecologically relevant land cover covariates (specific to species), all climate variables, protected area coverage, and the survey effort proxy. We then evaluated the full model for pairwise correlations and multicollinearity, sequentially removing highly correlated predictors ($|r| > 0.7$) and structurally collinear variables (VIF > 10). Continuous covariates were standardized (z-scaled) to facilitate comparison of coefficients within and across models. Prior to model ranking, we also constructed a limited set of ecologically relevant interaction terms involving protected area coverage.

Model ranking and selection were conducted for each response x block set combination using Akaike's Information Criterion corrected for small sampled size (AICc) (Akaike 1992, Burnham and Anderson 2004, Burnham et al. 2011, Morin et al. 2020). Among top candidate models where deltaAICc < 2, we then performed an assessment of uninformative parameters relative to a reference model (defined as the model with lowest AICc, with ties resolved by selecting the model with the fewest parameters). Although we expected protected area coverage and/or effort to be uninformative in some candidate models, we retained these predictors in all candidates through hard-coding due to their a priori ecological and structural relevance (Arnold 2010).

## Results

Of the 858 total blocks in the “DNR” set, 390 fell into the Colonization/Absence subset (Colonizations: 228, Absences: 162) and 468 into the Extinction/Persistence subset (Extinctions: 14, Persistences: 454). Of the 3337 total blocks in the “RLL” set, 2535 fell into the Colonization/Absence subset (Colonizations: 1168, Absences: 1367) and 802 into the Extinction/Persistence subset (Extinctions: 77, Persistences: 725).

Independent model ranking with AICc revealed multiple candidates (deltaAICc < 2) for each block set x response combination: DNRxColAbs = 10; DNRxExtPer = 25; RLLxColAbs = 37; RLLxExtPer = 14 (Supplemental Tables S1-S4). An analysis of uninformative parameters among top candidates (relative to the reference model) identified a few variables within the Extinction response model for both block sets, though none of them appeared in the reference models–the exception being the covariates for protected area and effort. Protected in both the RLL and DNR model was flagged as uninformative, while the species richness difference variable was flagged in only the latter; both covariates were retained within the reference model for further analysis due to their a priori ecological importance to our projects need to examine the effects of protected areas and structurally account for survey effort.

Across both block sets and response types, reference models explained substantial variation in apparent colonization and extinction probabilities for the Red-bellied Woodpecker in Wisconsin. While models showed no major violations in assumptions, diagnostics for the extinction models for both block sets merit closer examination. Extinction events were rare for this species, and such binned residual plots showed clustering at low fitted values, indicating models had low sensitivity to extinction (Supplemental Figure S2); effect directions are likely robust to inference, but magnitudes should be interpreted with caution. Moreover, because reference models represent only one parameter configuration among many top-ranked candidates, we focus on the interpretation of general patterns rather than precise coefficient estimates. For this limited analysis, we therefore emphasize the consistency and directionality of effects, rather than attempting to numerically quantify them.

Survey effort, represented by the change in species richness between the first and second Atlas period, was a strong predictor of apparent colonization and extinction in the minimally filtered “RLL” block set, but was weaker and/or nonsignificant in the more heavily thinned “DNR” block set, a pattern logically in line with the structure of the data itself. Long-term average summer maximum temperatures were consistently associated with both responses across block sets: per block, the probability of colonization increased with higher average maximum temperatures, while the probability of extinction was higher in blocks with lower long-term maximum temperatures. Land cover effects varied across models but showed a few key patterns: the probability of colonization declined with greater baseline cover of wetlands, mixed forest, and shrub-scrub habitats; interestingly, mixed forest cover appeared to be negatively associated with colonization probability.

We found minimal to no support for a main effect of protected area on apparent colonization and extinction among either block set (Figure 1). Within the RLL block set, however, an effect of protected area was supported through a number of interactions: positively with forest cover change and long-term maximum temperature, and negatively with wetlands cover and survey effort. Within the DNR block set, protected area coverage was slightly negatively associated with apparent colonization but interacted positively with forest cover change. Protected areas were not significantly associated with apparent extinction across either block set, suggesting said dynamic is more strongly structured by climate, land cover, and other effects not accounted for by these models.

## Discussion

We evaluated whether protected areas function as regional climate change refugia for a locally common species with Breeding Bird Atlas data, using Wisconsin and the Red-bellied Woodpecker as a test case. Across reference models, protected area coverage showed limited and context-dependent associations with apparent colonization and extinctions–our placeholders for range-shift dynamics given the temporal granularity of the WIBBA dataset. At the block-scale (25 km2), these findings suggest that protected areas do not provide buffering effects to colonization or extinction for breeding Red-bellied Woodpeckers in Wisconsin. A widely distributed generalist known to be expanding northward, it tracks that Red-bellied Woodpecker populations are likely not restricted to conditions found only on protected areas (Stallworth 2025). The negative association between mixed forest coverage and colonization probability is surprising, given the ecology of the Red-bellied Woodpecker, and may reflect unmeasured—or obscured, given our scale of inference (25km2)---aspects of forest structure, micro-habitat, or landscape context not captured by our models. Only by applying these methods to other species in the WIBBA dataset–such as specialists and data-poor species–will we begin to discern the true efficacy of these models in capturing the relationship between protected areas and climate-driven range-shifts.

Strong associations between the difference in species richness and apparent colonization or extinction were evident within the minimally filtered RLL dataset, underscoring the importance of subsetting decisions for inference when working with skewed citizen science datasets. Nevertheless, the direction of key covariate relationships was generally consistent across block sets. While analyses with additional species are needed, these preliminary results suggest that retaining a larger proportion of available data may be justified. In regional-scale analyses, bringing as much data to bear as possible is essential for preserving spatial coverage and statistical power.

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## Figures and Tables

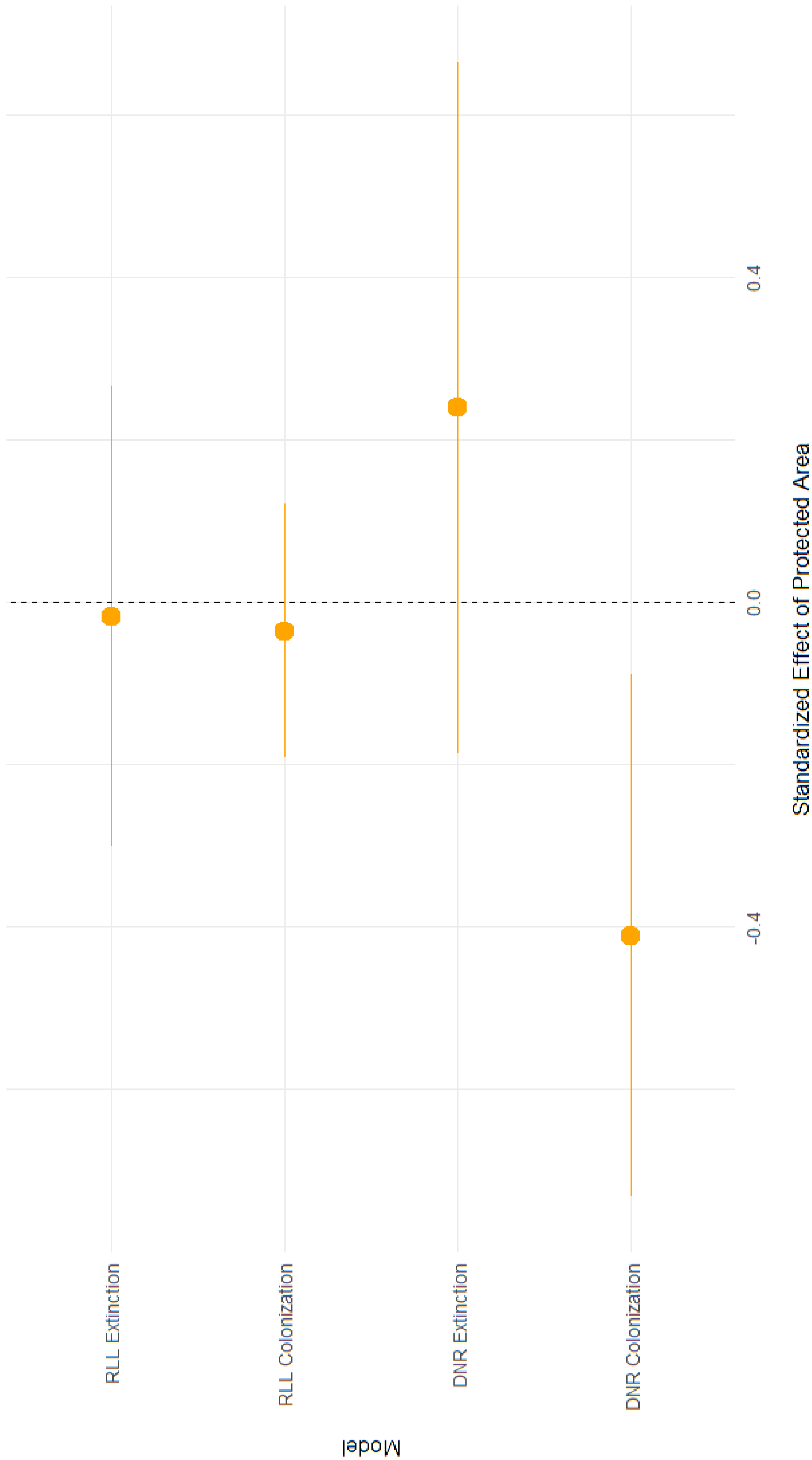


Figure 1. Standardzied main effect of protected area (PA) on apparent colonization and extinction for the Red-bellied Woodpecker among two survey unit subsets. Points represent effect estimates for each model, with horizantal lines representing 95% confidence intervals. PA main effects were generally small and often non-significant across models, with the exception of the DNR Colonization model, which had a modest, negative effect (estimate = -0.41, p = 0.013).

## Supplementary Materials

**Table S1.** Top models (37) (delta AICc < 2) for the RLL block set (N = 3337) x Colonization(xAbsence) response subset (n = 2535) for the Red-bellied Woodpecker; reference model is denoted by three asterisks (***).

| Model | logLik | K | AICc | delta | weight |
|---|---|---|---|---|---|
| ***col_abs ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z + wetlands_total_diff_z + forest_total_diff_z:pa_percent_z + pa_percent_z:sr_Diff_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1395.62 | 14 | 2819.409 | 0 | 0.009054 |
| col_abs ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + prcp_38yr_z + prcp_diff_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z + wetlands_total_diff_z + forest_total_diff_z:pa_percent_z + pa_percent_z:sr_Diff_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1393.63 | 16 | 2819.482 | 0.072826 | 0.00873 |
| col_abs ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + prcp_38yr_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z + wetlands_total_diff_z + forest_total_diff_z:pa_percent_z + pa_percent_z:sr_Diff_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1394.73 | 15 | 2819.656 | 0.246906 | 0.008002 |

| | | | | | |
|---|---|---|---|---|---|
| col_abs ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z + forest_total_diff_z:pa_percent_z + pa_percent_z:sr_Diff_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1396.87 | 13 | 2819.886 | 0.476674 | 0.007134 |
| col_abs ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + prcp_38yr_z + prcp_diff_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z + forest_total_diff_z:pa_percent_z + pa_percent_z:sr_Diff_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1394.87 | 15 | 2819.937 | 0.527289 | 0.006955 |
| col_abs ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + prcp_38yr_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z + forest_total_diff_z:pa_percent_z + pa_percent_z:sr_Diff_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1395.89 | 14 | 2819.938 | 0.52885 | 0.00695 |
| col_abs ~ (Intercept) + developed_total_base_z + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z + wetlands_total_diff_z + developed_total_base_z:pa_percent_z + forest_total_diff_z:pa_percent_z + pa_percent_z:sr_Diff_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1393.98 | 16 | 2820.184 | 0.774352 | 0.006147 |

| | | | | | |
|---|---|---|---|---|---|
| col_abs ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + prcp_38yr_z + prcp_diff_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z + wetlands_total_diff_z + forest_total_diff_z:pa_percent_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1395.05 | 15 | 2820.292 | 0.882385 | 0.005824 |
| col_abs ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + prcp_38yr_z + prcp_diff_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z + forest_total_diff_z:pa_percent_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1396.1 | 14 | 2820.377 | 0.967201 | 0.005582 |
| col_abs ~ (Intercept) + developed_total_base_z + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z + wetlands_total_diff_z + forest_total_diff_z:pa_percent_z + pa_percent_z:sr_Diff_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1395.1 | 15 | 2820.399 | 0.989629 | 0.00552 |
| col_abs ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + prcp_38yr_z + prcp_diff_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + tmin_diff_z + wetlands_total_base_z + wetlands_total_diff_z + forest_total_diff_z:pa_percent_z + pa_percent_z:sr_Diff_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1393.1 | 17 | 2820.438 | 1.028913 | 0.005413 |

| | | | | | |
|---|---|---|---|---|---|
| col_abs ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + prcp_diff_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z + wetlands_total_diff_z + forest_total_diff_z:pa_percent_z + pa_percent_z:sr_Diff_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1395.18 | 15 | 2820.555 | 1.145495 | 0.005106 |
| col_abs ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + prcp_38yr_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z + forest_total_diff_z:pa_percent_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1397.24 | 13 | 2820.621 | 1.211345 | 0.004941 |
| col_abs ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + prcp_38yr_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z + wetlands_total_diff_z + forest_total_diff_z:pa_percent_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1396.28 | 14 | 2820.722 | 1.312255 | 0.004698 |
| col_abs ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + prcp_38yr_z + prcp_diff_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + tmin_diff_z + wetlands_total_base_z + forest_total_diff_z:pa_percent_z + pa_percent_z:sr_Diff_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1394.3 | 16 | 2820.811 | 1.40187 | 0.004492 |

| | | | | | |
|---|---|---|---|---|---|
| col_abs ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + prcp_38yr_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + tmin_diff_z + wetlands_total_base_z + wetlands_total_diff_z + forest_total_diff_z:pa_percent_z + pa_percent_z:sr_Diff_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1394.35 | 16 | 2820.923 | 1.513943 | 0.004247 |
| col_abs ~ (Intercept) + developed_total_base_z + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z + forest_total_diff_z:pa_percent_z + pa_percent_z:sr_Diff_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1396.38 | 14 | 2820.933 | 1.523726 | 0.004226 |
| col_abs ~ (Intercept) + developed_total_base_z + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z + developed_total_base_z:pa_percent_z + forest_total_diff_z:pa_percent_z + pa_percent_z:sr_Diff_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1395.38 | 15 | 2820.958 | 1.549004 | 0.004173 |
| col_abs ~ (Intercept) + developed_total_base_z + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + prcp_38yr_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z + wetlands_total_diff_z + developed_total_base_z:pa_percent_z + forest_total_diff_z:pa_percent_z + pa_percent_z:sr_Diff_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1393.36 | 17 | 2820.972 | 1.562465 | 0.004145 |

| | | | | | |
|---|---|---|---|---|---|
| col_abs ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z + wetlands_total_diff_z + forest_total_diff_z:pa_percent_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1397.43 | 13 | 2821.007 | 1.597832 | 0.004072 |
| col_abs ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + tmin_diff_z + wetlands_total_base_z + wetlands_total_diff_z + forest_total_diff_z:pa_percent_z + pa_percent_z:sr_Diff_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1395.43 | 15 | 2821.043 | 1.634054 | 0.003999 |
| col_abs ~ (Intercept) + developed_total_base_z + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + prcp_38yr_z + prcp_diff_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z + wetlands_total_diff_z + developed_total_base_z:pa_percent_z + forest_total_diff_z:pa_percent_z + pa_percent_z:sr_Diff_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1392.4 | 18 | 2821.068 | 1.658924 | 0.00395 |
| col_abs ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z + forest_total_diff_z:pa_percent_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1398.48 | 12 | 2821.079 | 1.66954 | 0.003929 |

| | | | | | |
|---|---|---|---|---|---|
| col_abs ~ (Intercept) + developed_total_base_z + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + prcp_38yr_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z + wetlands_total_diff_z + forest_total_diff_z:pa_percent_z + pa_percent_z:sr_Diff_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1394.44 | 16 | 2821.093 | 1.683651 | 0.003901 |
| col_abs ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + prcp_38yr_z + prcp_diff_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + tmin_diff_z + wetlands_total_base_z + wetlands_total_diff_z + forest_total_diff_z:pa_percent_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1394.44 | 16 | 2821.106 | 1.696335 | 0.003877 |
| col_abs ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + prcp_38yr_z + prcp_diff_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + tmin_diff_z + wetlands_total_base_z + forest_total_diff_z:pa_percent_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1395.46 | 15 | 2821.117 | 1.707385 | 0.003855 |
| col_abs ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + prcp_38yr_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + tmin_diff_z + wetlands_total_base_z + forest_total_diff_z:pa_percent_z + pa_percent_z:sr_Diff_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1395.47 | 15 | 2821.129 | 1.719858 | 0.003831 |

| | | | | | |
|---|---|---|---|---|---|
| col_abs ~ (Intercept) + developed_total_base_z + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + prcp_38yr_z + prcp_diff_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z + wetlands_total_diff_z + forest_total_diff_z:pa_percent_z + pa_percent_z:sr_Diff_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1393.46 | 17 | 2821.172 | 1.763103 | 0.003749 |
| col_abs ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + prcp_38yr_z + prcp_diff_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + tmin_diff_z + wetlands_total_base_z + wetlands_total_diff_z + forest_total_diff_z:pa_percent_z + pa_percent_z:sr_Diff_z + pa_percent_z:tmax_38yr_z + pa_percent_z:tmin_diff_z + pa_percent_z:wetlands_total_base_z | -1392.45 | 18 | 2821.176 | 1.766778 | 0.003743 |
| col_abs ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + prcp_diff_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z + forest_total_diff_z:pa_percent_z + pa_percent_z:sr_Diff_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1396.51 | 14 | 2821.18 | 1.770175 | 0.003736 |
| col_abs ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + prcp_38yr_z + prcp_diff_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmin_diff_z + wetlands_total_base_z + forest_total_diff_z:pa_percent_z + pa_percent_z:sr_Diff_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1395.5 | 15 | 2821.19 | 1.780872 | 0.003716 |

| | | | | | |
|---|---|---|---|---|---|
| col_abs ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z + wetlands_total_diff_z + forest_mixed_base_z:pa_percent_z + forest_total_diff_z:pa_percent_z + pa_percent_z:sr_Diff_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1395.51 | 15 | 2821.215 | 1.805179 | 0.003671 |
| col_abs ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + grass_pasture_crop_base_z + pa_percent_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z + wetlands_total_diff_z + forest_total_diff_z:pa_percent_z + pa_percent_z:sr_Diff_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1395.57 | 15 | 2821.331 | 1.922069 | 0.003463 |
| col_abs ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + prcp_38yr_z + prcp_diff_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmin_diff_z + wetlands_total_base_z + forest_total_diff_z:pa_percent_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1396.6 | 14 | 2821.361 | 1.951366 | 0.003413 |
| col_abs ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + prcp_38yr_z + prcp_diff_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z + wetlands_total_diff_z + forest_mixed_base_z:pa_percent_z + forest_total_diff_z:pa_percent_z + pa_percent_z:sr_Diff_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1393.56 | 17 | 2821.373 | 1.963256 | 0.003392 |

| | | | | | |
|---|---|---|---|---|---|
| col_abs ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + grass_pasture_crop_base_z + pa_percent_z + prcp_38yr_z + prcp_diff_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z + wetlands_total_diff_z + forest_total_diff_z:pa_percent_z + pa_percent_z:sr_Diff_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1393.57 | 17 | 2821.375 | 1.965808 | 0.003388 |
| col_abs ~ (Intercept) + developed_total_base_z + forest_mixed_base_z + forest_total_diff_z + pa_percent_z + prcp_diff_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z + wetlands_total_diff_z + developed_total_base_z:pa_percent_z + forest_total_diff_z:pa_percent_z + pa_percent_z:sr_Diff_z + pa_percent_z:tmax_38yr_z + pa_percent_z:wetlands_total_base_z | -1393.58 | 17 | 2821.403 | 1.993678 | 0.003341 |

**Table S2**. Top models (9) (delta AICc < 2) for the RLL block subset (N = 3337) x Extinction(xPersistence) response subset (n = 802) for the Red-bellied Woodpecker; reference model is denoted by three asterisks (***).

| **Model** | **logLik.** | **K** | **AICc** | **delta** | **weight** |
|---|---|---|---|---|---|
| ***ext_per ~ (Intercept) + forest_total_diff_z + grass_pasture_crop_base_z + sr_Diff_z + tmax_38yr_z + tmin_diff_z | -184.518 | 6 | 381.1419 | 0 | 0.002644 |
| ext_per ~ (Intercept) + forest_total_diff_z + grass_pasture_crop_base_z + sr_Diff_z + tmax_38yr_z + tmin_diff_z + wetlands_total_diff_z | -183.888 | 7 | 381.9175 | 0.775682 | 0.001794 |

| | | | | | |
|---|---|---|---|---|---|
| ext_per ~ (Intercept) + forest_total_diff_z + grass_pasture_crop_base_z + pa_percent_z + sr_Diff_z + tmax_38yr_z + tmin_diff_z + pa_percent_z:tmax_38yr_z | -182.933 | 8 | 382.0478 | 0.90589 | 0.001681 |
| ext_per ~ (Intercept) + forest_total_diff_z + grass_pasture_crop_base_z + prcp_diff_z + sr_Diff_z + tmax_38yr_z + tmin_diff_z | -184.046 | 7 | 382.2336 | 1.091751 | 0.001532 |
| ext_per ~ (Intercept) + developed_total_base_z + forest_total_diff_z + grass_pasture_crop_base_z + sr_Diff_z + tmax_38yr_z + tmin_diff_z | -184.09 | 7 | 382.3203 | 1.178394 | 0.001467 |
| ext_per ~ (Intercept) + forest_total_diff_z + grass_pasture_crop_base_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + tmin_diff_z | -184.233 | 7 | 382.6076 | 1.465775 | 0.00127 |
| ext_per ~ (Intercept) + developed_total_base_z + forest_total_diff_z + grass_pasture_crop_base_z + sr_Diff_z + tmax_38yr_z | -185.334 | 6 | 382.7729 | 1.630998 | 0.00117 |
| ext_per ~ (Intercept) + forest_total_diff_z + grass_pasture_crop_base_z + pa_percent_z + sr_Diff_z + tmax_38yr_z + tmin_diff_z + forest_total_diff_z:pa_percent_z + pa_percent_z:tmax_38yr_z | -182.308 | 9 | 382.8436 | 1.701688 | 0.001129 |
| ext_per ~ (Intercept) + forest_total_diff_z + grass_pasture_crop_base_z + prcp_diff_z + sr_Diff_z + tmax_38yr_z + tmin_diff_z + wetlands_total_diff_z | -183.339 | 8 | 382.8586 | 1.716775 | 0.001121 |

| | | | | | |
|---|---|---|---|---|---|
| ext_per ~ (Intercept) + forest_total_diff_z + grass_pasture_crop_base_z + pa_percent_z + prcp_diff_z + sr_Diff_z + tmax_38yr_z + tmin_diff_z + pa_percent_z:tmax_38yr_z | -182.373 | 9 | 382.9731 | 1.831255 | 0.001058 |
| ext_per ~ (Intercept) + forest_total_diff_z + grass_pasture_crop_base_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z + tmin_diff_z | -184.427 | 7 | 382.9942 | 1.852354 | 0.001047 |
| ext_per ~ (Intercept) + forest_total_diff_z + grass_pasture_crop_base_z + sr_Diff_z + tmax_38yr_z + tmin_diff_z + wetlands_total_base_z | -184.436 | 7 | 383.0127 | 1.870829 | 0.001038 |
| ext_per ~ (Intercept) + forest_mixed_base_z + forest_total_diff_z + grass_pasture_crop_base_z + sr_Diff_z + tmax_38yr_z + tmin_diff_z | -184.44 | 7 | 383.0211 | 1.879225 | 0.001033 |
| ext_per ~ (Intercept) + developed_total_base_z + forest_total_diff_z + grass_pasture_crop_base_z + pa_percent_z + sr_Diff_z + tmax_38yr_z + tmin_diff_z + pa_percent_z:tmax_38yr_z | -182.442 | 9 | 383.1118 | 1.969924 | 0.000987 |

**Table S3.** Top models (10) (delta AICc < 2) for the DNR block set (n = 858) x Colonization(xAbsence) response subset (n = 390) for the Red-bellied Woodpecker; reference model is denoted by three asterisks (***).

| Model | logLik. | K | AICc | delta | weight |
|---|---|---|---|---|---|
| ***col_abs ~ (Intercept) + developed_total_base_z + forest_mixed_base_z + forest_total_diff_z + grass_pasture_crop_base_z + pa_percent_z + prcp_38yr_z + shrub_scrub_base_z + tmax_38yr_z + wetlands_total_base_z + forest_total_diff_z:pa_percent_z | -181.757 | 11 | 386.212 | 0 | 0.007274 |

| | | | | | |
|---|---|---|---|---|---|
| col_abs ~ (Intercept) + developed_total_base_z + forest_mixed_base_z + forest_total_diff_z + grass_pasture_crop_base_z + pa_percent_z + prcp_38yr_z + shrub_scrub_base_z + tmax_38yr_z + wetlands_total_base_z + forest_total_diff_z:pa_percent_z + pa_percent_z:tmax_38yr_z | -181.218 | 12 | 387.2633 | 1.051304 | 0.0043 |
| col_abs ~ (Intercept) + developed_total_base_z + forest_mixed_base_z + forest_total_diff_z + grass_pasture_crop_base_z + pa_percent_z + prcp_38yr_z + shrub_scrub_base_z + tmax_38yr_z + wetlands_total_base_z + forest_mixed_base_z:pa_percent_z + forest_total_diff_z:pa_percent_z | -181.254 | 12 | 387.3366 | 1.124571 | 0.004146 |
| col_abs ~ (Intercept) + developed_total_base_z + forest_mixed_base_z + forest_total_diff_z + grass_pasture_crop_base_z + pa_percent_z + prcp_38yr_z + shrub_scrub_base_z + tmax_38yr_z + wetlands_total_base_z + forest_mixed_base_z:pa_percent_z + forest_total_diff_z:pa_percent_z + pa_percent_z:tmax_38yr_z | -180.291 | 13 | 387.55 | 1.337943 | 0.003726 |
| col_abs ~ (Intercept) + developed_total_base_z + forest_mixed_base_z + forest_total_diff_z + grass_pasture_crop_base_z + pa_percent_z + prcp_38yr_z + shrub_scrub_base_z + sr_Diff_z + tmax_38yr_z + wetlands_total_base_z + forest_total_diff_z:pa_percent_z | -181.392 | 12 | 387.6114 | 1.399372 | 0.003613 |
| col_abs ~ (Intercept) + developed_total_base_z + forest_mixed_base_z + forest_total_diff_z + grass_pasture_crop_base_z + pa_percent_z + prcp_38yr_z + shrub_scrub_base_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z + forest_total_diff_z:pa_percent_z | -181.4 | 12 | 387.6282 | 1.416171 | 0.003583 |

| | | | | | |
|---|---|---|---|---|---|
| col_abs ~ (Intercept) + developed_total_base_z + forest_mixed_base_z + forest_total_diff_z + grass_pasture_crop_base_z + pa_percent_z + prcp_38yr_z + shrub_scrub_base_z + tmax_38yr_z + tmin_diff_z + wetlands_total_base_z + forest_total_diff_z:pa_percent_z | -181.427 | 12 | 387.6809 | 1.468909 | 0.00349 |
| col_abs ~ (Intercept) + developed_total_base_z + forest_mixed_base_z + forest_total_diff_z + grass_pasture_crop_base_z + pa_percent_z + prcp_38yr_z + tmax_38yr_z + wetlands_total_base_z + forest_total_diff_z:pa_percent_z | -183.581 | 10 | 387.7427 | 1.530647 | 0.003384 |
| col_abs ~ (Intercept) + developed_total_base_z + forest_mixed_base_z + forest_total_diff_z + grass_pasture_crop_base_z + pa_percent_z + prcp_38yr_z + shrub_scrub_base_z + tmax_38yr_z + wetlands_total_base_z + forest_total_diff_z:pa_percent_z + pa_percent_z:wetlands_total_base_z | -181.468 | 12 | 387.7637 | 1.551654 | 0.003348 |
| col_abs ~ (Intercept) + developed_total_base_z + forest_mixed_base_z + forest_total_diff_z + grass_pasture_crop_base_z + pa_percent_z + prcp_38yr_z + shrub_scrub_base_z + tmax_38yr_z + wetlands_total_base_z + developed_total_base_z:pa_percent_z + forest_total_diff_z:pa_percent_z | -181.591 | 12 | 388.0097 | 1.797662 | 0.002961 |

**Table S4.** Top models (25) (delta AICc < 2) for the DNR block set (n = 858) x Extinction(xPersistence) response subset (n = 468) for the Red-bellied Woodpecker; reference model is denoted by three asterisks (***).

| Model | logLik. | K | AICc | delta | weight |
|---|---|---|---|---|---|
| ***ext_per ~ (Intercept) + developed_total_base_z + forest_total_diff_z + tmax_38yr_z | -49.9752 | 4 | 108.0369 | 0 | 0.002101 |

| | | | | | |
|---|---|---|---|---|---|
| ext_per ~ (Intercept) + developed_total_base_z + forest_total_diff_z + pa_percent_z + tmax_38yr_z + forest_total_diff_z:pa_percent_z | -48.0993 | 6 | 108.3809 | 0.344009 | 0.001769 |
| ext_per ~ (Intercept) + developed_total_base_z + forest_total_diff_z + sr_Diff_z + tmax_38yr_z | -49.3057 | 5 | 108.7412 | 0.704324 | 0.001477 |
| ext_per ~ (Intercept) + developed_total_base_z + forest_total_diff_z + pa_percent_z + tmax_38yr_z | -49.3142 | 5 | 108.7583 | 0.721428 | 0.001465 |
| ext_per ~ (Intercept) + developed_total_base_z + forest_total_diff_z + tmax_38yr_z + tmax_diff_z | -49.4563 | 5 | 109.0426 | 1.005679 | 0.001271 |
| ext_per ~ (Intercept) + developed_total_base_z + forest_total_diff_z + tmax_38yr_z + wetlands_total_diff_z | -49.4588 | 5 | 109.0474 | 1.010517 | 0.001267 |
| ext_per ~ (Intercept) + developed_total_base_z + forest_total_diff_z + pa_percent_z + tmax_38yr_z + developed_total_base_z:pa_percent_z + forest_total_diff_z:pa_percent_z | -47.4566 | 7 | 109.1566 | 1.119741 | 0.0012 |
| ext_per ~ (Intercept) + developed_total_base_z + forest_total_diff_z + grass_pasture_crop_base_z + tmax_38yr_z | -49.5254 | 5 | 109.1807 | 1.143837 | 0.001186 |
| ext_per ~ (Intercept) + developed_total_base_z + forest_total_diff_z + prcp_38yr_z + tmax_38yr_z + wetlands_total_base_z | -48.5479 | 6 | 109.2781 | 1.241198 | 0.001129 |
| ext_per ~ (Intercept) + developed_total_base_z + forest_total_diff_z + prcp_38yr_z + tmax_38yr_z | -49.5912 | 5 | 109.3123 | 1.275427 | 0.00111 |

| | | | | | |
|---|---|---|---|---|---|
| ext_per ~ (Intercept) + forest_total_diff_z + prcp_38yr_z + tmax_38yr_z + wetlands_total_base_z | -49.6158 | 5 | 109.3614 | 1.324564 | 0.001083 |
| ext_per ~ (Intercept) + prcp_38yr_z + shrub_scrub_base_z + tmax_38yr_z + wetlands_total_base_z | -49.6345 | 5 | 109.399 | 1.362091 | 0.001063 |
| ext_per ~ (Intercept) + developed_total_base_z + forest_total_diff_z + tmax_38yr_z + wetlands_total_base_z | -49.6649 | 5 | 109.4597 | 1.422806 | 0.001031 |
| ext_per ~ (Intercept) + developed_total_base_z + forest_total_diff_z + shrub_scrub_base_z + tmax_38yr_z | -49.6735 | 5 | 109.4768 | 1.439935 | 0.001023 |
| ext_per ~ (Intercept) + developed_total_base_z + forest_total_diff_z + sr_Diff_z + tmax_38yr_z + tmax_diff_z | -48.7124 | 6 | 109.607 | 1.570107 | 0.000958 |
| ext_per ~ (Intercept) + developed_total_base_z + forest_total_diff_z + sr_Diff_z + tmax_38yr_z + wetlands_total_diff_z | -48.7151 | 6 | 109.6124 | 1.575569 | 0.000956 |
| ext_per ~ (Intercept) + developed_total_base_z + forest_total_diff_z + pa_percent_z + sr_Diff_z + tmax_38yr_z | -48.736 | 6 | 109.6543 | 1.61738 | 0.000936 |
| ext_per ~ (Intercept) + developed_total_base_z + forest_total_diff_z + prcp_38yr_z + tmax_38yr_z + wetlands_total_diff_z | -48.7749 | 6 | 109.732 | 1.69515 | 0.0009 |
| ext_per ~ (Intercept) + developed_total_base_z + forest_total_diff_z + pa_percent_z + tmax_38yr_z + tmax_diff_z + forest_total_diff_z:pa_percent_z | -47.7514 | 7 | 109.7463 | 1.709463 | 0.000894 |
| ext_per ~ (Intercept) + developed_total_base_z + forest_total_diff_z + pa_percent_z + sr_Diff_z + tmax_38yr_z + forest_total_diff_z:pa_percent_z | -47.7637 | 7 | 109.7708 | 1.73392 | 0.000883 |

| | | | | | |
|---|---|---|---|---|---|
| ext_per ~ (Intercept) + developed_total_base_z + forest_total_diff_z + pa_percent_z + prcp_38yr_z + tmax_38yr_z + forest_total_diff_z:pa_percent_z | -47.8359 | 7 | 109.9152 | 1.878354 | 0.000821 |
| ext_per ~ (Intercept) + prcp_38yr_z + shrub_scrub_base_z + tmax_38yr_z + wetlands_total_base_z + wetlands_total_diff_z | -48.8717 | 6 | 109.9255 | 1.888672 | 0.000817 |
| ext_per ~ (Intercept) + developed_total_base_z + forest_total_diff_z + pa_percent_z + tmax_38yr_z + developed_total_base_z:pa_percent_z | -48.874 | 6 | 109.9302 | 1.893373 | 0.000815 |
| ext_per ~ (Intercept) + developed_total_base_z + forest_total_diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_diff_z | -48.8777 | 6 | 109.9377 | 1.9008 | 0.000812 |
| ext_per ~ (Intercept) + developed_total_base_z + forest_total_diff_z + tmax_38yr_z + tmax_diff_z + wetlands_total_base_z | -48.9069 | 6 | 109.9959 | 1.959074 | 0.000789 |

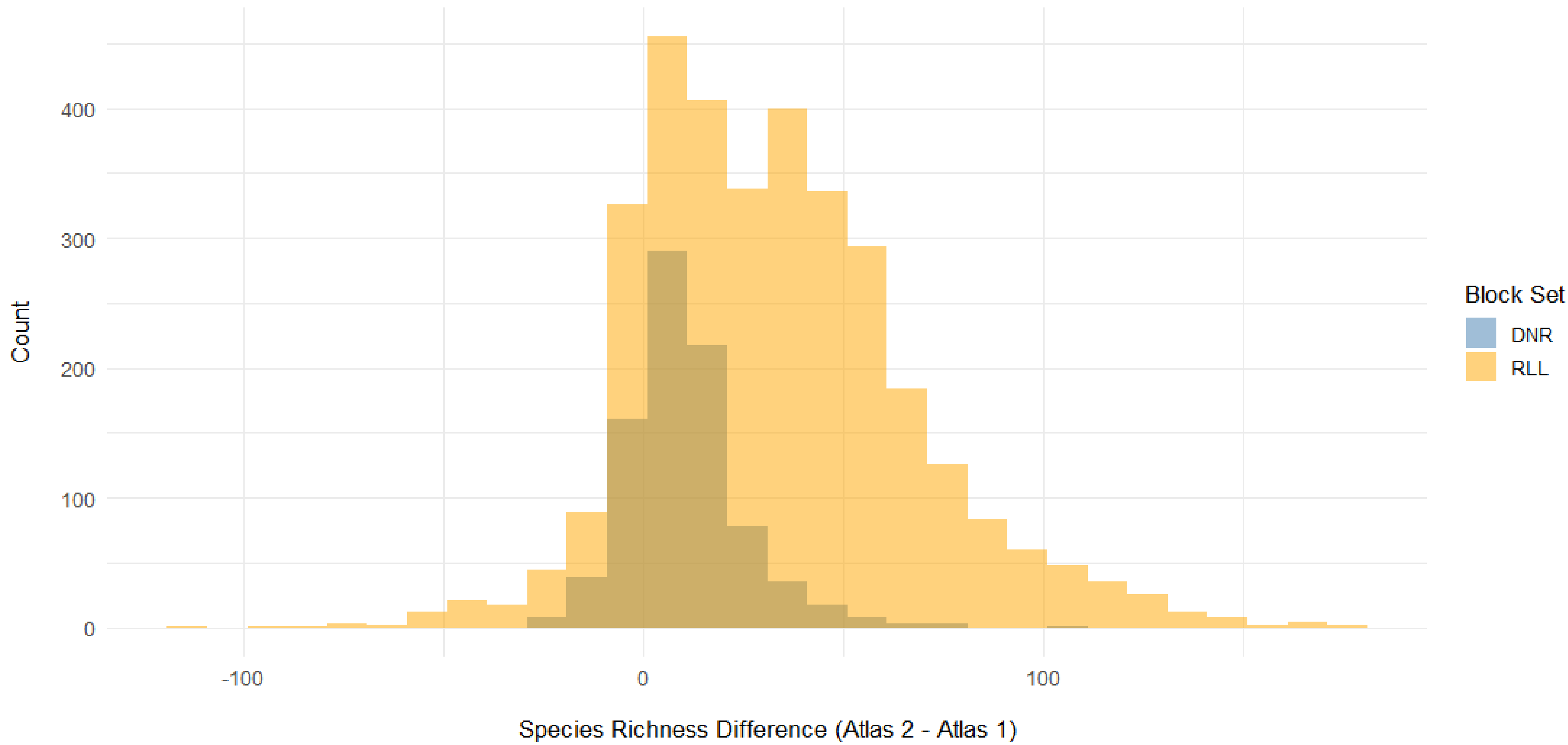


Figure S1. Distribution of difference in species richness between Wisconsin Breeding Bird Atlas 1 (1995-2000) and 2 (2015-2019) between two different survey block subsets (All Blocks, N = 7056; RLL, n = 2535; DNR, n = 858). Overall, blocks in the second Atlas were surveyed more comprehensively than in Atlas 1, resulting in higher-per-block species richness in Atlas 2 generally. The minimally filtered RLL block set retains a significant number of survey units with high species richness differences compared to the heavily filtered DNR block set, which largely controlled for these coverage discrepancies.

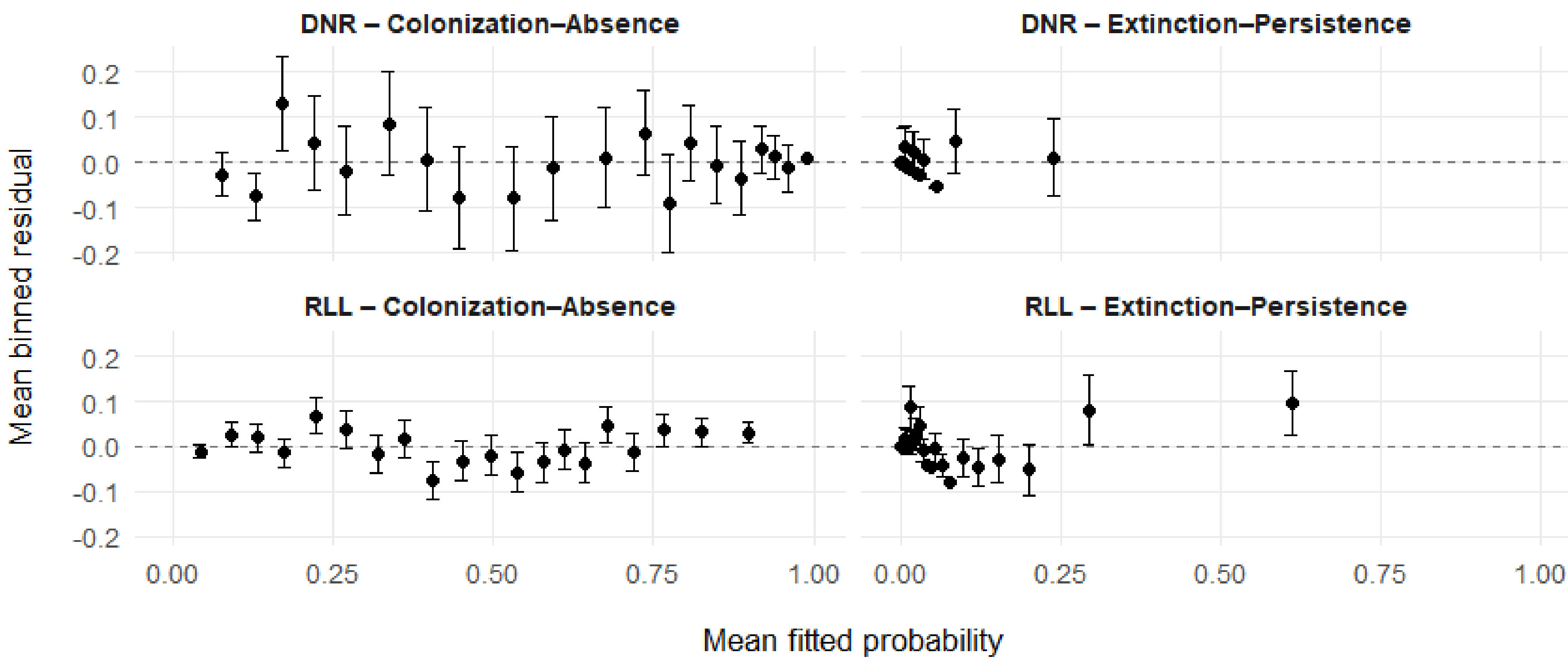


Figure S2. Binned residual diagnostic plots for each block set x response logistic model combination. Each point represents the mean residual within a group of fitted probabilities, with vertical error bars representing a +/- 1 standard error of the mean residual. Aggregation of of residuals at low fitted probabilities for the Extinction/Persistence data models reflects the rarity of extinction events within the data, rather than any issue with model fit.